

The New $\sigma_{tot}(\Sigma p)$ Data, the new PDG fit to hadron total cross sections and the TCP alternative

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Abstract

The new SELEX measurement $\sigma_{tot}(\Sigma p) = 36.96 \pm 0.65$ at $P = 609$ GeV/c and the new 1998 Particle-Data-Group Regge (PDG) analysis of hadron total cross sections with an additional even-signature-exchange contribution recall the 1975 two-component-Pomeron model (TCP), which introduced such an additional term and predicted $\sigma_{tot}(\Sigma p) = 37.07$ mb. in 1975 as well as fitting all the same data now fit by PDG with fewer free parameters and predicting $\sigma_{tot}(\Sigma p)$, (not predicted by PDG) at lower energies. The additional contribution confuses the extraction of the Pomeron intercept from data in the 600 GeV range and its dynamical origin is still unclear. But its surprising systematics suggests an interesting origin.

I. IMPLICATIONS OF A THIRD COMPONENT

The new SELEX [1] result $\sigma_{tot}(\Sigma p) = 36.96 \pm 0.65$ at $P = 609$ GeV/c, is in surprising agreement with the 1975 prediction $\sigma_{tot}(\Sigma p) = 37.07$ mb. from the Two-Component-Pomeron model (TCP). This model arose from an analysis of the systematics of hadron-nucleon total cross section data [2] which showed the necessity of including a new third term in addition to the commonly used Pomeron and leading Reggeon contributions. The new accepted Particle-Data-Group (PDG) Regge analysis of hadron total cross sections [3] has

now also shown that three terms are needed to fit the existing data. It is thus of interest to recall the TCP model which not only fits the same data with different and fewer parameters determined in 1975 and not changed since; it also successfully predicted hyperon-nucleon cross sections not predicted by PDG, now including the new SELEX result.

Both PDG and TCP use a Regge term which decreases with energy roughly like $s^{-0.5}$, and a universal Pomeron term which increases with energy roughly like $s^{0.1}$. They also use an additional even-signature term. with an intermediate energy variation ($s^{-0.34}$ in the PDG model and $s^{-0.2}$ in the TCP model). Both analyses express the total hadronic cross section for hadron A on a proton in the form

$$\sigma Ap = X_{Ap}s^\epsilon + Y_{1Ap}s^{-\eta_1} + Y_{2Ap}s^{-\eta_2} \quad (1.1)$$

PDG sets

$$X_{Ap}^{PDG} = X_{Ap}; \quad Y_{1Ap}^{PDG} = Y_{1Ap}; \quad Y_{2Ap}^{PDG} = -Y_{2Ap} \quad (1.2)$$

where X_{AB} , Y_{1AB} , Y_{2AB} , ϵ , η_1 , η_2 are determined by fitting data.

TCP sets

$$\begin{aligned} X_{Ap}^{TCP} &= X \cdot N_q(A); & Y_{1Ap}^{TCP} &= Y_1 \cdot N_q(A) \cdot N_n(A) \\ Y_{2Ap}^{TCP} &= Y_2 \cdot [2N_{\bar{u}}(A) + N_{\bar{d}}(A)]; & \eta_2 &= -0.5 \end{aligned} \quad (1.3)$$

where the coefficients X , Y_1 and Y_2 are universal for all hadrons, $N_q(A)$ is the total number of valence q and \bar{q} in A , $N_n(A)$ is the total number of nonstrange valence q and \bar{q} in A , $N_{\bar{u}}(A)$ and $N_{\bar{d}}(A)$ are respectively the numbers of valence \bar{u} and \bar{d} in A .

Both PDG and TCP fix parameters by fitting data, but there are many fewer free parameters in TCP than in PDG. In PDG the coefficients X_{Ap} , Y_{1Ap} and Y_{2Ap} are determined by fitting data and are independent of one another, except for the equality of the isoscalar pomeron X_{Ap} couplings between all states in the same isospin multiplet.

The particle-antiparticle relations in Y_2 are very different. In PDG Y_2 has only the odd signature ρ and ω trajectories, and no contributions from the even signature f and A_2

trajectories. TCP uses the known exchange degeneracy of the ρ , ω , f and A_2 trajectories and therefore follows the Harari-Rosner [6] duality description in which $Y_2 = 0$ in exotic channels which have no resonances.

In the original TCP notation

$$\begin{aligned} \sigma_{Ap}^{TCP} = & \frac{N_q(A)}{2} \cdot \sigma_1(P_{lab}/20)^\epsilon + \\ & \frac{N_q(A) \cdot N_n(A)}{2} \cdot \sigma_2(P_{lab}/20)^{-\delta} + \\ & + [2N_{\bar{u}}(A) + N_{\bar{d}}(A)] \cdot \sigma_R(P_{lab}/20)^{-0.5} \end{aligned} \quad (1.4)$$

where the values determined by fitting the data available in 1975 and not changed since were $\sigma_1 = 13$ mb, $\epsilon = 0.13$, $\sigma_2 = 4.4$ mb, $\delta = 0.2$ and $\sigma_R = 1.75$ mb.

In both PDG and TCP the exponents ϵ and η_1 are determined by fitting data with no theoretical input beyond the relations between different hadrons already expressed in the formulas; i.e. the particle-antiparticle relations in PDG and the quark-counting relations in TCP. One sees immediately that there are many fewer free parameters in TCP and that the particle-antiparticle relations in the Regge term proportional to Y_2 are very different between the two formulas.

That two models with different parametrizations can fit the same data comes as no surprise. The data for $\sigma_{tot}(pp)$ vs. $\log(s)$ are very well fit by a parabola which is uniquely determined by three parameters [4]. Thus these data have been shown to be easily fit equally well by different two-Reggeon models which have four free parameters, two magnitudes and two exponents.

Because the TCP couplings are universal, the expression (1.4) predicts the hyperon-nucleon cross sections with the parameters above determined in 1975 by the other experimental cross sections and no further input.

II. WHERE IS THE PHYSICS? WHAT CAN WE LEARN?

In 1975 this question was investigated by making the most naive assumptions about the two leading terms, the Pomeron and the leading trajectories, subtracting these contributions from the total cross sections and looking at what remained. The surprising result, shown on fig. 4 of ref. [2], is still impressive. The additional contribution is universal above 20 GeV/c. The pp , $\bar{p}p$, $\pi^\pm p$ and $K^\pm p$ cross sections lie on a universal curve with scaling factors of 9:4:2 for protons, pions and kaons. This is just the product of the total number of quarks and the number of nonstrange quarks, the scaling factor one would obtain for a Pomeron-f cut or for a triple-regge term in which the beam hadron couples to a Pomeron and an f.

What is this additional contribution? There is still no satisfactory explanation. But it continues to fit data and has predictive power. Note in particular the predictions for hyperon-nucleon cross sections then not available. The predicted scaling factors for Σp and Ξp are 6 and 3 and they work, including the new SELEX [1] measurement of $\sigma_{tot}(\Sigma p)$.

The initial motivation leading to TCP was to search beyond the simple pole approximation in Regge phenomenology. This first order approximation in strong interactions could not be the whole story. The total cross section data were already sufficiently precise to suggest a search for new higher-order physics. The ansatz of a double-exchange contribution to hadron-nucleon scattering with the flavor dependence of a pomeron-f cut or a triple-Regge diagram with a pomeron and an f coupled to the incident hadron led to a series of relations in remarkable agreement with experiment [8]. The present situation only reinforces the initial reaction to these results [9] “I don’t believe a word of this crazy model, but the numbers are impressive. You must find a better explanation”. Since then more and more impressive numbers have been found, [2,10–12] but no better explanation. A contribution with the flavor dependence of a Pomeron-f cut and an s dependence fit by a unique decreasing power fits more and more data, but there is yet no credible explanation for this s dependence.

The most naive assumptions used for the leading terms were that the Pomeron simply counts quarks and is fitted by a rising power of s and that the leading Regge contribution

counts Harari-Rosner Duality Diagrams [6] and decreases like $s^{-(1/2)}$. Plugging these assumptions and fixing the five universal parameters by fitting the 1975 data up to 200 GeV/c gave the TCP model with the same parameters that still fit data accumulated since 1975.

We now examine these assumptions from the point of view of QCD.

This model can be described in modern QCD language [4] in terms of a hierarchy of contributions inspired by large N_c QCD: (1) multigluon exchange, (2) planar quark diagrams, (3) nonplanar quark-exchange diagrams.

The Pomeron is described by multigluon exchanges which do not know about flavor and are the same for pion and kaons and for protons and hyperons. The additive quark counting giving the 3/2 factor between baryons and mesons is obtained from color algebra for two-gluon and three-gluon exchanges [14]. There is no firm justification for neglecting higher exchanges but it fits the data.

The leading Regge exchanges are described Harari-Rosner duality diagrams are just the planar quark-exchange diagrams which are the leading contributions in large- N_c QCD [4]. This immediately incorporates $s - t$ duality [15], since exotic channels which have no resonances have no contribution from planar quark diagrams.

The third term then comes from more complicated non-planar quark diagrams. Why these should scale in the way that they do is still open. But this term should be absent in processes like $\phi - n$ which cannot have such quark-exchange diagrams because there are no valence quarks in the beam and target with the same flavor. There are no extensive data for $\phi - n$. But we can consider as “gedanken” $\sigma_{tot}(\phi^- p)$ the linear combination

$$\sigma_{ged}(\phi^- p) \equiv \sigma_{tot}(K^+ p) + \sigma_{tot}(K^- p) - \sigma_{tot}(\pi^- p) \quad (2.1)$$

which is equal to $\sigma_{tot}(\phi^- p)$ in the quark model. The data for “gedanken” $\sigma_{tot}(\phi^- p)$ are shown on fig. 4 of ref. [2] and seen to rise monotonically and can be fit by a single power of s as expected for a cross section which has neither planar nor nonplanar quark exchange diagrams and has only a Pomeron contribution. The contribution of the third term to “gedanken” $\sigma_{tot}(\phi^- p)$ is shown on fig. 4 of ref. [2] to be consistent with zero above 10 GeV/c. But the

ansatz still has no convincing basis and no firm connection with QCD beyond hand waving.

TCP pinpoints open questions and puzzles not fully understood about the relation between meson and baryon structure, the link between Regge phenomenology and QCD, and how the remarkable successes of the constituent quark model can be eventually described by QCD.

TCP assumes $s - t$ duality [15] in which $\sigma_{tot}(pp)$ is exotic and has no leading Regge contribution. The decrease in $\sigma_{tot}(pp)$ with energy observed at low energies thus indicates the existence of another decreasing contribution in addition to leading Regge. Assuming that this contribution is described by the double exchange ansatz and determining its parameters by fitting $\sigma_{tot}(pp)$ then gives unique nontrivial predictions for all other exotic cross sections; e.g. $\sigma_{tot}(K^+p)$, $\sigma_{tot}(\Sigma p)$, $\sigma_{tot}(\Xi p)$ and the linear combination $\sigma_{tot}(K^-p) - \sigma_{tot}(\pi^-p)$. The linear combination “gedanken” $\sigma_{tot}(\phi^-p)$ has no double exchange contribution and is predicted to rise monotonically with the same single power of s used to fit the rising term in $\sigma_{tot}(pp)$. All predictions continue to agree with new experimental data with no further adjustment of the five TCP parameters. Particularly impressive was the factor $2/3$ predicted before the hyperon-nucleon cross sections were measured which contradicted all the conventional wisdom.

$$\begin{aligned}\sigma_{tot}(\pi^-p) - \sigma_{tot}(K^-p) &= (2/3)\{\sigma_{tot}(pp) - \sigma_{tot}(\Sigma p)\} = \\ &= (2/3)\{\sigma_{tot}(\Sigma p) - \sigma_{tot}(\Xi p)\}\end{aligned}\tag{2.2}$$

The remarkable success of naive TCP for all hadron-nucleon cross sections was summarized in the 1981 Moriond report of the CERN hyperon experiment [13].

The simple systematics like the factor $3/2$ between hyperon-nucleon and meson-nucleon strangeness differences and the monotonic rise with s of the linear combinations which have no simple quark exchange diagrams suggest the the existence of some simple explanation based on QCD, even if the TCP ansatz is wrong. Further investigations may provide new insight into how QCD makes hadrons from quarks and gluons and should be encouraged.

III. EXPERIMENTAL EVIDENCE THAT MESONS AND BARYONS ARE MADE OF THE SAME QUARKS

The large number of relations between meson-nucleon and baryon-nucleon total cross sections which agree with experiment suggest that mesons and baryons are made of the same constituent quarks in the $q\bar{q}$ and $3q$ configurations. We summarize these here and examine them from different points of view to hopefully provide clues for theoretical explanations.

There is first the simple additive quark prediction,

$$\delta_{AQM} \equiv (2/3) \cdot \sigma_{tot}(pp) - \sigma_{tot}(\pi^- p) \leq 7\% \quad (3.1)$$

There is then the TCP prediction

$$\begin{aligned} \sigma_{tot}(\pi^- p) - \sigma_{tot}(K^- p) &= \\ &= (1/3)\sigma_{tot}(pp) - (1/2)\sigma_{tot}(K^+ p) \end{aligned} \quad (3.2)$$

Both of these are confirmed by data up to $P_{lab} = 310$ GeV/c. There are as yet no data available for a complete set of all these reactions at the same single energy above $P_{lab} = 310$ GeV/c.

There are the TCP predictions for baryon-nucleon cross sections from meson-baryon cross sections at 100 GeV/c where data are available.

$$\begin{aligned} 38.5 \pm 0.04 \text{mb.} &= \sigma_{tot}(pp) = \\ &= 3\sigma_{tot}(\pi^+ p) - (3/2)\sigma_{tot}(K^- p) = 39.3 \pm 0.2 \text{mb.} \end{aligned} \quad (3.3)$$

$$\begin{aligned} 33.3 \pm 0.31 \text{mb.} &= \sigma_{tot}(\Sigma p) = \\ &= (3/2)\{\sigma_{tot}(K^+ p) + \sigma_{tot}(\pi^- p) - \sigma_{tot}(K^- p)\} = \\ &= 33.6 \pm 0.16 \text{mb.} \end{aligned} \quad (3.4)$$

$$\begin{aligned} 29.2 \pm 0.29 \text{mb.} &= \sigma_{tot}(\Xi p) = \\ &= (3/2)\sigma_{tot}(K^+ p) = 28.4 \pm 0.1 \text{mb.} \end{aligned} \quad (3.5)$$

$$\begin{aligned}
& \sigma_{tot}(\Omega^- p) = \\
& = (3/2)\{\sigma_{tot}(K^+ p) - \sigma_{tot}(\pi^- p) + \sigma_{tot}(K^- p)\}
\end{aligned} \tag{3.6}$$

Another interesting way to view the data is to compare the strange and nonstrange quark contributions to the to baryon-nucleon and meson-nucleon total cross sections extracted using the additive quark model

Let $\sigma(fN)_H$ denote the total cross section on a nucleon target, for a single quark of flavor f in a hadron H on a nucleon target, where f may be strange s or nonstrange n and H may be a baryon B or a meson M . The additive quark model gives

$$\sigma(nN)_B = \frac{1}{3} \cdot \sigma(pN) = 12.9 \pm 0.01 mb. \tag{3.7}$$

$$\begin{aligned}
\sigma(sN)_B &= \frac{1}{3}\{\sigma(\Sigma N) + \sigma(\Xi N) - \sigma(pN)\} = \\
&= 7.7 \pm 0.1 mb.
\end{aligned} \tag{3.8}$$

$$\begin{aligned}
\sigma(nN)_M &= \frac{1}{2}\{\sigma(\pi N) - \sigma(\bar{K}N) + \sigma(KN)\}m = \\
&= 11.2 \pm 0.05 mb.
\end{aligned} \tag{3.9}$$

$$\begin{aligned}
\sigma(sN)_M &= \frac{1}{2}\{\sigma(\bar{K}N) - \sigma(\pi N) + \sigma(KN)\} = \\
&= 7.75 \pm 0.05 mb.
\end{aligned} \tag{3.10}$$

where we have assumed $\sigma(sN)_M = \sigma(\bar{s}N)_M$.

We find the surprising result that the contribution of the strange quarks is the same to both meson-nucleon and baryon-nucleon total cross sections, but that the contribution of the nonstrange quarks is the less for meson-nucleon than for baryon-nucleon total cross sections. This immediately gives rise to speculations that nonstrange quarks are more complicated than strange quarks because they can have a pion cloud. However, there has been no success in carrying this argument further quantitatively. Instead we obtain the following surprising relations, which go to the heart of the TCP ansatz; namely that one single mechanism is responsible for the breakings of both SU(3) flavor symmetry and the additive quark model.

$$\sigma(nN)_B - \sigma(nN)_M = 1.69 \pm 0.05mb. \quad (3.11)$$

$$\frac{1}{2}\{\sigma(nN)_M - \sigma(sN)_M\} = 1.73 \pm 0.04mb. \quad (3.12)$$

The difference between the contributions of nonstrange quarks to baryon-nucleon and meson-nucleon cross sections is equal to the difference between the contributions of non-strange and strange quarks to meson-nucleon cross sections.

This as yet unexplained connection between the deviation from SU(3) symmetry and the deviation from the Levin-Frankfurt AQM 3/2 ratio for baryons and mesons has been expressed by the experimentally satisfied relation [2]

$$\sigma_{tot}(\pi^-p) - \sigma_{tot}(K^-p) = (1/3)\sigma_{tot}(pp) - (1/2)\sigma_{tot}(K^+p) \quad (3.13)$$

This has been rearranged to give

$$\begin{aligned} \sigma_{ged}(\phi^-p) &\equiv \sigma_{tot}(K^+p) + \sigma_{tot}(K^-p) - \sigma_{tot}(\pi^-p) = \\ &= (3/2)\sigma_{tot}(K^+p) - (1/3)\sigma_{tot}(pp) \end{aligned} \quad (3.14)$$

The expressions on both sides of this relations are found experimentally not only to be equal but to increase monotonically with energy and fit by a single power. This fits in with the picture that $\sigma_{ged}(\phi^-p)$ contains only a pure Pomeron contribution. But that the right hand side which is a linear combination of meson and baryon cross sections behaves in the same way suggests some sort of universality for the Pomeron.

We also find that the difference between the contributions of nonstrange and strange quarks to baryon-nucleon cross sections is greater by a factor of (3/2) than the corresponding difference for meson-nucleon cross sections.

$$\sigma(nN)_B - \sigma(sN)_B = 5.15 \pm 0.07mb. \quad (3.15)$$

$$\frac{3}{2}\{\sigma(nN)_M - \sigma(sN)_M\} = 5.2 \pm 0.1mb. \quad (3.16)$$

As soon as one begins to think about some dynamical origin for these relations one encounters a very perplexing question. Why is there seemingly such a simple relation between hadron-nucleon total cross sections, when any credible scattering model suggests that they should be very different and depend upon radii and geometrical considerations, not simply quark counting? Perhaps a relevant interesting analogy is in the relation between hadronic electromagnetic form factors and electric charges. The form factors of pions, nucleons and other hadrons are complicated and very different from one another. But their total electric charge is simple and given by adding up the charges of their constituent quarks. Rutherford scattering measures total charge. Does universality of contributions to $\sigma_{tot}(Hp)$ suggest measurements of some kinds of total charge in which the microscopic details are somehow not important?

IV. CONCLUSIONS

We conclude by listing a hierarchy of the experimental systematics found in this phenomenological analysis and the questions to be resolved by further experiments at higher energies:

A. Summary of experimental systematic regularities

1. Odd signature universality

ρ universality (Sakurai) - conserved isospin current

ω universality - related to ρ by U(2)

Energy dependence - like $s^{-1/2}$

2. Exchange degeneracy - No exotic contributions

Only planar quark diagrams contribute

3. Universal Pomeron - Counts quarks

Given by amplitude with no quark exchanges

$$\sigma_{ged}(\phi^- p) = \sigma_{tot}(K^+ p) + \sigma_{tot}(K^- p) - \sigma_{tot}(\pi^- p)$$

4. What's left?

Universal contribution scaling like Pomeron-f cut

Scaling factors of 9:4:2 like for protons, pions and kaons.

Extrapolated to 6 and 3 for Σp and Ξp - predict data!

But what is it?

B. Interesting questions to be decided by future experiments

1. Does the ad-hoc third component continue to explain both the deviation from SU(3) symmetry and the deviation from the Levin-Frankfurt AQM 3/2 ratio for baryons and mesons; i.e. do $\sigma_{tot}(\pi^-p) - \sigma_{tot}(K^-p)$ and $(1/3)\sigma_{tot}(pp) - (1/2)\sigma_{tot}(K^+p)$ continue to remain equal at higher energies?
2. Do both the SU(3) breaking and the deviation from 3/2 go to zero at high energies or does one or both level off. Data at around 200 GeV/c indicate that $\sigma_{tot}(\pi^-p) - \sigma_{tot}(K^-p)$ might be leveling off while $(1/3)\sigma_{tot}(pp) - (1/2)\sigma_{tot}(K^+p)$ continues to decrease with increasing energy. But the differences are not convincing and better data at higher energies should easily resolve this question.
3. Is there a universal Pomeron that holds for all hadrons with a 3/2 ratio between baryon and meson couplings? Do $\sigma_{ged}(\phi^-p)$ and $(3/2)\sigma_{tot}(K^+p) - (1/3)\sigma_{tot}(pp)$ continue to be equal and rise monotonically like a pure Pomeron contribution? To answer this question reliably one must go to high enough energies so that the contribution of the third component becomes negligible.

C. Bottom Line

There is much yet to learn from future experiments about how QCD makes hadrons out of quarks and gluons.

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